Primitive earth: so near to hell †

ROBERT JASTROW
Director, NASA's Goddard Space Flight Centre, New York, USA

One of the most surprising things about the atmosphere of the earth is that it is totally unrelated to the layer of vapours and gases that surrounded our planet when it was first formed about forty-six hundred million years ago. The evidence is based on the fact that the earth's present atmosphere contains hardly any of the very abundant 'rare' gases which exist in the sun's atmosphere and elsewhere in the cosmos as we know it from studying the spectra of other stars. Neon, in particular, is one of the most abundant elements in the universe. Yet neon is very rare in our atmosphere; it is under-abundant by a factor of more than a million, compared to the amount that should be present if the earth's atmosphere today were the direct descendant of the layer of gases that must have surrounded it as it condensed out of the gases of the solar nebula forty-six hundred million years ago.

The present atmosphere of the earth must have appeared in some other way. To a student of the earth, the only logical possibility is that the gases of the atmosphere have been exhaled from the solid body of the earth as vapours during the course of our planet's history. The oceans of the earth are also the result of exhalation of water vapour through cracks and fissures in the crust.

If we examine the content of gases in volcanoes, for example, we find that it is 85%water vapour, 10% carbon dioxide, 5% nitrogen and 1% trace constituents. The 85% water composition adds up, over the course of forty-six hundred million years, to precisely the 2·7 km of average water depth that cover the face of our planet. The nitrogen that dominates our atmosphere today corresponds to just that 5% that is exhaled through cracks and volcanoes. Carbon dioxide, which should be a major element according to the rate of exhalation of this substance in volcanoes, is not abundant in the atmosphere—less than 1%. It is this scarcity of carbon dioxide that makes our planet a pleasant place to live in contrast to the 'hell-hole' that is the planet Venus today.

Not only do we know that the present atmosphere of the earth is secondary, but we also know that this secondary atmosphere is quite different from that which surrounded the earth during the first billion years of its history.

One of the reasons we are sure of that is that the earth's atmosphere has a great deal of oxygen today, and we know that this oxygen is not exhaled through cracks in the earth's crust, but is the product of life on this planet—of plant life and of photosynthesis.

At the beginning of the earth's history, the atmosphere was, in a chemical sense, the exact opposite of the heavily oxidizing, oxygen-rich atmosphere that we have today. It is believed that the gases that came up through the crust at that time, as volcanic emissions, consisted of hydrogen, which is a reducing substance, ammonia, which is a combination of nitrogen and hydrogen, and methane, a combination of carbon and hydrogen. These gases are present today only in trace amounts as a product of barnyard decompositions and other modern consequences of the terrestrial scene.

The reason for their erstwhile abundance and present scarcity is connected with a very interesting circumstance that surprisingly involves the centre of the earth. When the earth was newly formed it had a great deal of iron in it, but that iron probably had not run to the centre yet to form a hot molten iron core. Much of it was distributed throughout the outer layers of the earth's crust as free iron. This free iron took up the oxygen from the water that was in the earth's crust. That oxidized the iron from ferrous to ferric, leaving hydrogen, the other constituent of the water. Thus, instead of today's abundant water, the hydrogen was emitted from the earth's crust in abundance, and with it came the hydrogen-rich gases ammonia and methane.

Now that is an extremely interesting result,

†This article is based on a lecture broadcast by Dr Robert Jastrow on 9 March 1970 on the BBC Third Programme, by kind permission of the BBC.

because it is precisely out of this mixture of gases—hydrogen, methane and ammonia, plus some water—that biochemists have manufactured the building blocks of life. In experiments that simulate the passage of lightning or solar ultraviolet through the primitive reducing hydrogen-rich atmosphere of the earth, biochemists have produced the amino acids and nucleotides that make up proteins and DNA and RNA.

Experiments and calculations on the dissociation of these hydrogen-rich molecules, and particularly on the rate at which the dissociated hydrogen will escape to space, indicate that the hydrogen in the earth's atmosphere and the hydrogen-rich gases could not have remained here in abundance throughout our history. It is no surprise that we have a different atmosphere today. The investigations indicate that the hydrogen could not have lasted more than a hundred million, or at the very most a thousand million, years. By that time, this light gas, very weakly bound by the earth's gravity, would have disappeared. But one hundred million years probably is long enough for the first steps to have taken place along the path of chemical evolution from non-life to life; perhaps the beginnings of a primitive kind of plant life were already in existence by the time the hydrogen had leaked away substantially. Once that happened, evolution no longer needed (if one doesn't mind speaking of it as if it had a purpose) the hydrogen-rich atmosphere of the young earth. It had served its purpose. And the fact that it disappeared didn't matter. Photosynthesis continued, and plants evolved and flourished, exhaling oxygen as a part of their metabolism, as plants do today.

The level of the oxygen in the atmosphere built up rapidly as a result of the photosynthesis occurring in these primitive plants. The build-up had an important secondary effect on the history of the earth's atmosphere. The oxygen layer prevented the water in the oceans of the earth from disappearing by providing a shielding layer which screened out the particular wavelengths of ultraviolet radiation from the sun that would have penetrated to the surface of the earth, and in the course of our whole history would probably have removed the oceans by breaking-up water molecules into hydrogen and oxygen. The point is that the earth's gravity is strong enough to hold its oxygen, but it is not strong enough to hold its hydrogen for forty-six hundred or thirty-six hundred million years. Through plant photosynthesis, oxygen was manufactured, which in turn preserved the water which was needed for the further development of life.

That is the story of our planet and its atmosphere. Possessed of this knowledge regarding the history of the earth's atmosphere and the intimate manner in which it is related to the development of life on our planet, one immediately wonders what the prospects are for a similar atmospheric development and perhaps for the development of a similar kind of life chemistry on any one of the hundreds of thousands of millions of other planets that we think surround us in our galaxy and in other galaxies. It is very important to enlarge the context of one's discussion of the subject beyond our solar system because there are only a few earth-like planets here, and only one is in really good shape to support us. But there are one hundred thousand million other stars in our galaxy and each of them, or most of them, as far as we can tell, contains a family of planets. Among them there must be some fraction of planets which are very similar to the earth. In addition, there are ten thousand million other galaxies, each containing one hundred thousand million families of planets, that are within range of our largest telescopes—an overwhelming multitude.

The question arises then: are we alone in this galaxy or this corner of the cosmos? Is the chance of life developing on an earth-like planet as small as one in a trillion, or is it as high as one in one hundred thousand? A little illumination on this basic mystery, this most interesting question in all science, is provided by data we have acquired recently on the atmosphere and the surface conditions of Venus.

Venus is nearly identical to the earth in size and in mass; it has 95% of our mass and almost the same force of gravity. It pulls at its atmospheric gases with no more or less strength than our planet does. It is a little nearer to the sun, but presumably was made of similar gases and grains of dust as it condensed out of the solar nebula forty-six hundred million years ago. It must have had the same kind of gases—carbon dioxide, nitrogen, water vapour, hydrogen, *etc*—coming up through cracks in its crust and through volcanoes during its history. We would therefore expect it to have an atmosphere similar to the earth's today, and a somewhat milder but very pleasant climate. The romantic hope has always flourished that beneath the clouds that cover Venus there was a vigorous growth of plants and animals on a planetary body whose average temperatures at the latitude of London would be 80 °F the year round.

These hopes were shattered by a series of earth and space observations, culminating in the Soviet and American spacecraft missions to Venus in 1967 and 1969. These flights proved that the surface of Venus is not pleasant; the temperature there is no less than 800 °F, hot enough to melt lead and making it inconceivable that any form of life should exist on Venus, even at the poles. Furthermore, the atmosphere of Venus, unlike that of the earth, is dominated by carbon dioxide, and it possesses this gas in the crushing abundance of 100 times the atmospheric pressure at the surface of the earth. That is, the pressure at the surface of Venus, instead of being, say, 15 pounds per square inch, is nearly a ton per square inch. The carbon dioxide seals in the planet's heat and prevents it from escaping to space—the so-called greenhouse effect—which explains why the planet is so hot and inhospitable.

Why does the atmosphere of Venus have 70000 times more carbon dioxide than the atmosphere of the earth? If we can answer that question, then we may find out how wide the range of conditions must be on a planet in order for life to develop. We may learn, for example, whether the earth would also have developed into a 'hell-hole' if it had been formed two or three million miles closer to the sun.

There is no definite theory or answer to the question I have posed, but there is some fairly convincing speculation as to how Venus diverged early in its history from the path followed by the earth.

The idea is based on two experimental facts. The first, which gives a clue to the answer, is the amazing coincidence that the thick layer of carbonates in the earth's crust—compounds of carbon with oxygen and other substances—and the amount of carbon in these carbonates is the same as the amount of carbon in the total carbon dioxide content of the Venus atmosphere. That makes us wonder whether some chemical reaction may not have taken place on the earth that removed the carbon dioxide, converting it to carbonates—reactions which could not occur on Venus.

That thought leads to a second thought: marine animals convert carbon dioxide, which they breathe in from the ocean water, to carbonates, and then when they die their bodies sink to the ocean floor and are compacted into sedimentary rocks. They take up enough carbon dioxide today to account for the removal of all the carbon dioxide which is coming up to the earth's surface in the form of volcanic gases.

Does this chain of reasoning work? There is no life on Venus; therefore no carbon dioxide is removed and thus the greenhouse effect made the planet too hot. But then we are in a circular argument because we are about to say 'too hot to support life' and that brings us back to the starting point.

We can break out of the circle by making use of a last experimental fact. The rocks in the earth's crust, and presumably the rocks in the crust of Venus as well, also have the capacity for absorbing carbon dioxide from the atmosphere and converting it to carbonates by reactions not involving the presence of life. The key element in this observed fact is that the rate at which the rocks of a planet's crust absorb carbon dioxide depends very sensitively on the temperature of the rocks. If the rocks are cool, they absorb the carbon dioxide very effectively and remove it from the atmosphere; but, if they are hot, they absorb it very poorly or perhaps not at all. In fact, if they are heated enough, they will give up carbonates to the atmosphere in the form of carbon dioxide going in the reverse direction.

Now let us look at the earth and Venus when they were young planets. Venus was a little warmer than the earth, being a little closer to the sun. The mean temperature on its surface can be calculated. If it was a barren body of rock at that time, without clouds, the mean temperature on its surface can be calculated to have been 330 K. The mean temperature on the surface of the earth at that time, on the other hand, was about 250 or 260 K.

The earth would have absorbed carbon dioxide, according to experiments, about a thousand times more rapidly than Venus. Therefore, as the carbon dioxide was emitted into the atmosphere from the crust of the earth, it would have built up rather slowly. On Venus, it would have built up rapidly enough to raise the temperature a bit above 330 K, because of the greenhouse effect. When the temperature goes above 330 K, the absorbing influence of the rocks of Venus on its atmospheric carbon dioxide diminishes further, and a runaway process begins which can easily lead from the temperate conditions on Venus as a young barren planet to the furnace that exists on its surface today.

As a final thought, I cannot avoid contemplating the fact that this chain of reasoning, if correct, suggests that the gate through which life must pass on an earth-like planet, at the beginning, is far narrower than we would have supposed a few years ago, and that the chances of life developing on those hundreds of thousands of millions of other planets around us in our galaxy or in the cosmos is not as high as we might have thought. We may not be alone, but we are a somewhat rarer kind of organism than one might have thought a short time ago.

Underwater cables

In a special presentation the Science Museum, London, celebrates one of the great human endeavours of the Victorian Age, the development of underwater cables. In this exhibition an attempt is made to recapture some of the feeling the Victorians had for this enterprise. The social consequences are presented along with the evidence to technological achievement. The development of the specialized technology is shown from its beginning to the complex submerged cable repeaters of today.

The exhibition is open during normal museum hours until 3 February 1974.